

REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-0188	
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1. REPORT DATE (DD-MM-YYYY) 13-10-2011		2. REPORT TYPE Conference Paper		3. DATES COVERED (From - To)	
4. TITLE AND SUBTITLE The Effect of Swirl on Gas-Centered Swirl Coaxial Injector Sprays				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) Malissa D..A. Lightfoot, S.Alexander Schumaker, and Stephen A. Danczyk (AFRL/RZSA), Larry A. Villasmil (Rochester Inst. Of Technology)				5d. PROJECT NUMBER	
				5f. WORK UNIT NUMBER 50260538	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Air Force Research Laboratory (AFMC) AFRL/RZSA 10 E. Saturn Blvd. Edwards AFB CA 93524-7680				8. PERFORMING ORGANIZATION REPORT NUMBER AFRL-RZ-ED-TP-2011-409	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Air Force Research Laboratory (AFMC) AFRL/RZS 5 Pollux Drive Edwards AFB CA 93524-7048				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S NUMBER(S) AFRL-RZ-ED-TP-2011-409	
12. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution unlimited (PA #11882).					
13. SUPPLEMENTARY NOTES For presentation at the JANNAF 2011 Joint Subcommittee Meeting, Huntsville, AL, 5-9 Dec 2011.					
14. ABSTRACT Gas-centered swirl coaxial injector design criteria and scaling laws have been developed by AFRL over the last several years. These studies have predominately focused on the measurement and behavior of the liquid film and its relation to atomization efficiency. The spread and quality of the spray as well as its stability have received less attention. These parameters are the focus here and are shown to support the conclusions drawn from the liquid film studies. The spray width is used as the primary metric as the effects of swirl level, momentum flux ratio, liquid flow rate and inlet size/number are examined. The results suggest that the designer should aim for higher levels of swirl and momentum flux ratio and lower liquid mass flow rates to produce more stable sprays with better atomization.					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Dr. M.D.A. Lightfoot
Unclassified	Unclassified	Unclassified	SAR	12	19b. TELEPHONE NUMBER (include area code) N/A

THE EFFECT OF SWIRL ON GAS-CENTERED SWIRL COAXIAL INJECTOR SPRAYS

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ABSTRACT

Gas-centered swirl coaxial injector design criteria and scaling laws have been developed by AFRL over the last several years. These studies have predominately focused on the measurement and behavior of the liquid film and its relation to atomization efficiency. The spread and quality of the spray as well as its stability have received less attention. These parameters are the focus here and are shown to support the conclusions drawn from the liquid film studies. The spray width is used as the primary metric as the effects of swirl level, momentum flux ratio, liquid flow rate and inlet size/number are examined. The results suggest that the designer should aim for higher levels of swirl and momentum flux ratio and lower liquid mass flow rates to produce more stable sprays with better atomization.

INTRODUCTION

Storable propellants, as opposed to cryogenics, have been the focus of much next-generation rocket engine design. Of particular interest have been liquid hydrocarbon fuels, such as RP-2. The mixture ratio of heavy hydrocarbon (RP) engines is substantially different than those of typical cryogenics, such as hydrogen. As a result, the flow rates of hydrocarbon injectors are different than their cryogenic counterparts. The change in propellants, then, necessitates a change of injectors.

One type of injector that has proven effective in hydrocarbon-fueled engines is the gas-centered swirl coaxial (GCSC) injector [1]. A GCSC injector uses a high relative velocity between the gas and liquid to atomize the liquid. In this type of injector, a swirling, annular liquid film is formed via tangential inlets while the unswirled gas enters axially. The liquid and gas are initially separated by a thin lip; the lip helps to ensure a well-developed liquid sheet is formed prior to initial contact of the two phases. A typical GCSC injector is depicted in Fig. 1.

Despite prior use, the design criteria for this injector were not well documented. In recent years AFRL has studied these injectors extensively, and they have developed some design criteria [2]. These studies have focused on developing a physics-based understanding of the atomization process at the single-element level and, through this understanding, the development of scaling laws and design criteria. These, in turn, reduce the time and costs associated with engine development.

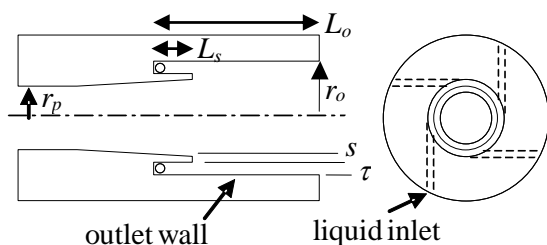


Figure 1. Schematic representation of a gas-centered swirl coaxial injector

The scaling law was developed through cold-flow studies, using water and nitrogen as stimulants, and applies to GCSC injectors and other injectors with strong gas-phase participation in the atomization process [3]. It predicts the atomization performance. This performance can be related to mixing efficiency and, ultimately, engine efficiency [3]. Because the spray produced by GCSC injectors (as well as most other rocket

injectors) is optically dense, mixing efficiency cannot be measured directly. Instead, earlier studies have relied on the length of the film formed within the injector as a measure of atomization performance. As a result, the earlier works have focused on scaling and design from the standpoint of the film and the ability to atomize the liquid. There is another aspect of the process that is of importance—the behavior and spread of the spray once it exits the injector. Also, examination of the spray should verify the claims that film length is related to atomization efficiency.

While recommendations and scaling have been reported in the past, very little work has been done to elucidate the effects of swirl number. A recent study found that atomization efficiency is not affected by swirl until the swirl number is at or very near zero [4]. These studies only considered the atomization efficiency via studies of the film length, however—they did not consider the behavior and spread of the spray. Sprays, particularly, spray angles, of simplex (aka pressure swirl) atomizers—essentially GCSC injectors with no gas flow—have been studied extensively [5-7], and give clues as to the effects of swirl. However, the gas flow will fundamentally alter the behavior of the spray. This alteration is easily seen—simplex atomizers produce hollow-core sprays while GCSC injectors produce solid sprays [9]. Some studies have also examined coaxial injector sprays with respect to swirl; however, spreading and spray angles are less often reported [8]. Again, though, while some clues as to swirl's impact are available, the fundamental spray evolution differs from GCSC injectors. In a coaxial swirl element the gas flow in many ways prevents the spread of the swirling liquid. A GCSC injector has the spray drawn into the center by the gas flow. The momentum transfer from the gas to the liquid film and droplets (changing the velocity vector) is the only process limiting the spray angle of the GCSC injectors. Without the central gas flow, the spray angle is almost 180° with the face of the injector being wetted; with the gas flow, even at lower flow rates than typical operating conditions, the spray angle is substantially more modest.

This current work focuses on the general character of the spray and the spray width and stability. Since specific measurements of the spray's internal structure are currently impractical to obtain (due to high optical density), the border of the spray, obtained from shadowgraphy images, is used as a comparative tool; it proves an idea of the spray's spread and how mixing with other elements might proceed in a rocket engine. Changes in the liquid inlet geometry and operating conditions receive primary consideration. Other geometric parameters, such as initial film thickness, are considered to be secondary effects; however, this assumption has not been verified here. Also briefly considered is the computational modeling of the film profile when no swirl is present.

EXPERIMENTAL SET-UP

The results reported here are from high-speed shadowgraphy of gas-centered swirl coaxial injectors (GCSC) with differing internal geometries. A typical GCSC injector is shown in Fig. 1. The injector tested is modular allowing easy variation in initial film thicknesses and lip height prior to gas and liquid contact. Changing injector bodies allows alteration of the outlet diameter and liquid inlet geometry. Here, though, only the lip thickness and liquid inlets are altered. The basic, constant geometry parameters are given in Table 1. Table 2 lists the variations in lip thickness and inlet geometry while Fig. 2 illustrates the differing liquid inlet configurations.

Throughout these tests, stimulants are used instead of actual propellants. Demineralized water is used to simulate the fuel, and nitrogen is used to simulate the oxidizer. Flow rates are controlled via critical flow orifices—sonic nozzle for the gas and cavitating venturis for the liquid. The orifices and the pressure transducers needed to set flow rates are calibrated at least yearly. Flow rates are considered to be accurate within 0.25%. In all cases, the sprays were ejected into atmospheric conditions. Due to the elevation of the testing facility, this pressure is typically near 0.9 atm.

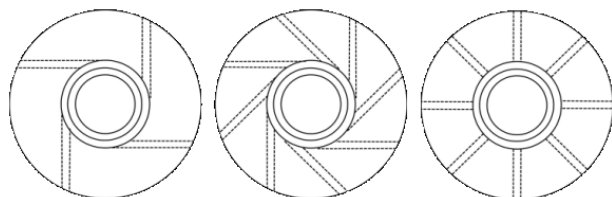


Figure 2. Schematic of the four different inlets investigated here. Only one of the 8-hole tangential inlet is shown; the other's layout is identical but the inlet diameter is different.

Outlet Radius, r_o	9.53 inch
Gas Post Radius, r_p	12.7 inch
Injector Cup, L_o	31.7 inch
Sheltered Length, L_s	3.17 inch
Initial Film Thickness, τ	1.65 inch

Table 1. Reports the fixed geometric parameters for the GCSC injectors tested.

Geometry Name	Lip Height (mm)	Inlet Area (mm^2)	Inlet Number	R_A
8A1D	2.41	7.50	8	0.261
4A1D	2.41	7.54	4	0.299
4A1N	1.52	7.54	4	0.299
8A2D	2.41	15.1	8	0.406
NSD	2.41	7.50	8	1.000

Table 2. The variable geometries and their names are given. R_A is the ratio of tangential to total velocity.

Test Name	m_g (g/s)	m_l (g/s)	MFR	R_A
8A1D-M1L2	66.8	45.1	62	0.261
8A2D-M1L2	32.1	45.3	63	0.406
4A1D-M1L2	57.3	45.8	67	0.299
8A1D-M2L1	56.9	36.2	81	0.261
4A1D-M2L2	67.1	45.4	81	0.299
8A2D-M2L2	65.2	60.4	82	0.406
NSD-M2L1	8.5	27.6	84	1.000
4A1N-M2L1	59.1	32.7	88	0.299

Table 3. The operating conditions and test names are given. In the test names M represents the momentum flux ratio (MFR) while L represented the liquid mass flow rate (m_l) and the numbers following represent the group to which the test belongs. Geometry names are explained within Table 2.

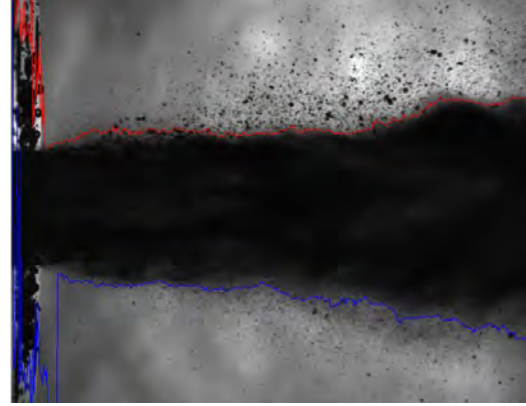


Figure 3. An example frame from test 4A1D-M2L2 is shown with the traced boundaries overlaid.

Sprays were backlit using a 500 W, collimated, DC light source. A diffuser was used to create a more uniform background. High speed video was taken using a Phantom v7.3 camera. The 14-bit images were taken at a framing rate of 6006 frames per second and shutter speeds between 20 and 30 microseconds (depending on extinction due to spray density).

Data was extracted from the videos using an in-house-written Matlab code. The main process is a basic edge-detection technique using image segmentation. The image is broken into spray and background segments. Otsu's method is used to determine the threshold for segmentation. The implementation of Otsu's method built in to Matlab's 2008b version was used [10-11]. Because the spray and the background are not steady, the threshold values determined from the segregation methods are not identical across the frames of a single test-condition video. As a result, the instantaneous values, i.e. the values determined from each specific frame, were not the only values considered. An additional threshold value was determined from the average over the full range of frames examined. Differences between instantaneous and averaged values were small, however. As a result, only the instantaneous results are presented here (the choice is made because they have slightly less noise than the averaged threshold values).

Once the segmentation (threshold) value was determined, it was used to produce a binary (black and white) image. The Matlab function *bwboundaries* was then employed to find the outline of the spray [11]. An 8-connected neighborhood with Matlab's "no holes" setting was used. Only the main body of the spray was considered, any traced areas prior to the injector outlet or of isolated droplets or droplet groups were discarded. A sample image with the traced boundaries overlaid is shown as Fig. 3.

Several parameters of importance were measured from the spray boundary. Here, though, only the width and its deviation are discussed. The width was calculated as the difference between the two boundaries in the images. Values are reported up to 50 mm downstream with photographs showing somewhat farther, approximately 70 mm. Due to noise from droplets clinging to the injector outlet and other issues, widths are not reported until 10 mm downstream of the injector exit (images show the

injector exit). While measurements were made for each frame, the results presented and discussed here are averages performed over 1000 frames.

Estimating the uncertainty in the boundary location determined from the images is nontrivial. An earlier study suggested that the boundary uncertainty was around ± 0.25 mm for each boundary [12]. However, that study was at a different resolution, had a different lighting mechanism, and averaged more images than the current one. The lighting here is more consistent and the resolution is slightly finer. These changes could improve uncertainty. However, the averaging of less images decreases the confidence level. At present, then, the uncertainty is thought to be on the same order as earlier studies, ± 0.5 mm in width.

RESULTS AND DISCUSSION

Table 3 contains the conditions at which spray video was collected. As shown in Table 2 and Fig. 2, four different liquid inlets were considered. These inlets produced four different swirl numbers. In all but the no-swirl case, the tangential velocity is large compared to the total velocity, so a “traditional” swirl number ratioing these two velocities will not be used. Instead the ratio of axial to total liquid velocity (R_A) will be used [5]. The axial velocity is calculated from the known cross-sectional area under the lip and simple mass conservation arguments. The total velocity is calculated by assuming that the momentum of the liquid is conserved between the tangential liquid injector holes and the liquid cup exit. Values of R_A are given in Table 2.

It is unlikely that swirl is the only aspect of the injector operation that impacts the spray. Studies of simplex atomizers have found only slight changes in spray angle (spreading) with numbers or areas of inlets, but liquid flow rate has been shown to have strong impacts [6, 7]. Studies of atomization efficiency in GCSC injectors have found that the most important parameters for determining atomization behavior is the momentum flux ratio [5]. This ratio is expected to play a large role here as well. With these considerations in mind, tests were chosen to isolate the effect of swirl number and the effect of momentum flux ratio. Some comparison of changes in liquid mass flow rate will be considered, but these also involve changes in swirl number of lip geometry, so conclusions are preliminary.

EFFECT OF SWIRL NUMBER

Obviously, as the swirl increases, the tangential velocity of the liquid will increase. While the liquid film is atomized prior to exiting the injector cup, the droplets may retain some of the film’s tangential momentum. Centripetal forces would, then, cause injectors with greater swirl number to have wider sprays. Additionally, if there is a momentum exchange between the gas and liquid, the gas would be more likely to acquire tangential velocity from a film with greater swirl; conversely, the liquid velocity

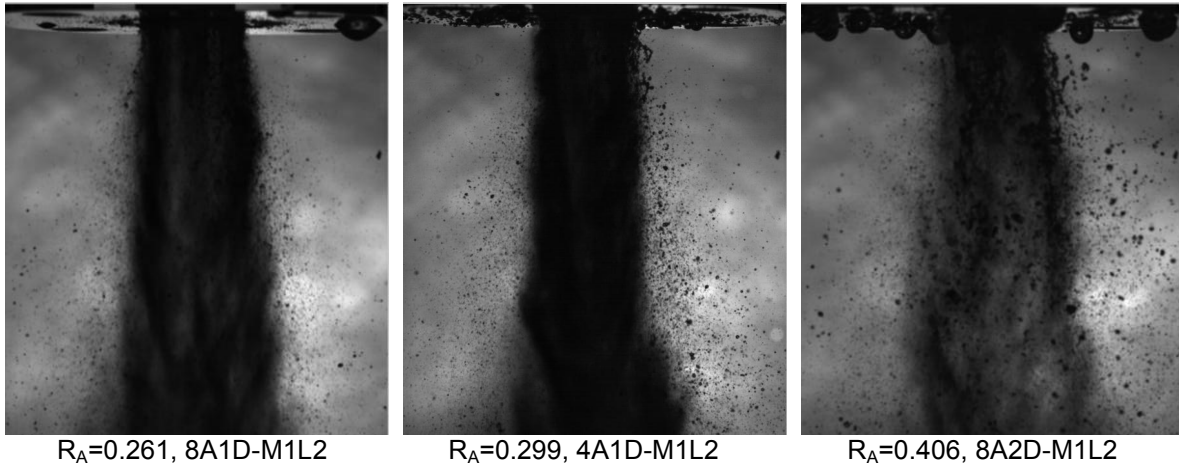


Figure 4. The swirl level has an impact on the quality of the spray as seen by the change in size and number of structures on the periphery of the spray.

vector would be less likely to straighten if the tangential velocity was larger. All of the sprays examined here have relatively large swirl number except the case with no swirl.

Prior to considering width, the general character of sprays with different swirl numbers is considered. Figure 4 shows a single frame from three sprays with similar momentum flux ratios and liquid flow rates but different R_A (swirl). The lowest swirl, highest R_A , case is noticeably different from the other two sprays. The spray with less swirl is not as optically dense and has larger droplets along its periphery than the sprays with more swirl. Similar results are shown in Fig. 5 which compares a spray with no swirl to one with the highest swirl. Again, these sprays have similar mass flow rates and momentum flux ratios. The no-swirl case is a markedly worse spray than the swirling case—a sheet still exists at the exit and there are no fine droplets forming a dark core. This lack of core makes measuring the spray width impossible. An additional note here, however, is that the gas flow rate of the no-swirl geometry is substantially lower than for the highest swirl. This extreme difference may explain some of the changes; however, as discussed in the next section, modest changes in gas flow rate do not have visible effects.

There is also a difference in the stability of these sprays. Unstable sprays, sprays with a lot of variation, are undesirable because they can cause local hot (or cold) spots and may feed into combustion

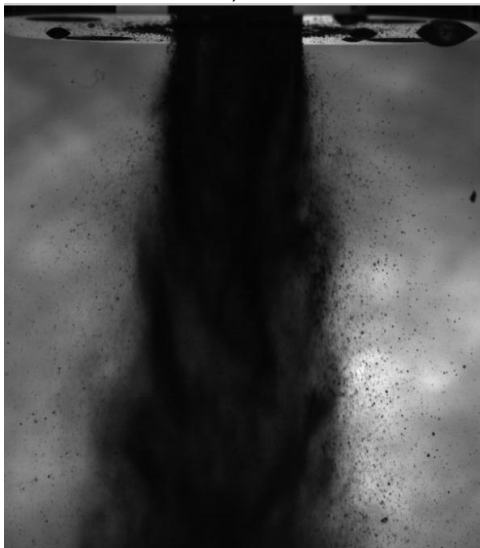


Figure 5. The atomization quality is strongly degraded in the case with no swirl.

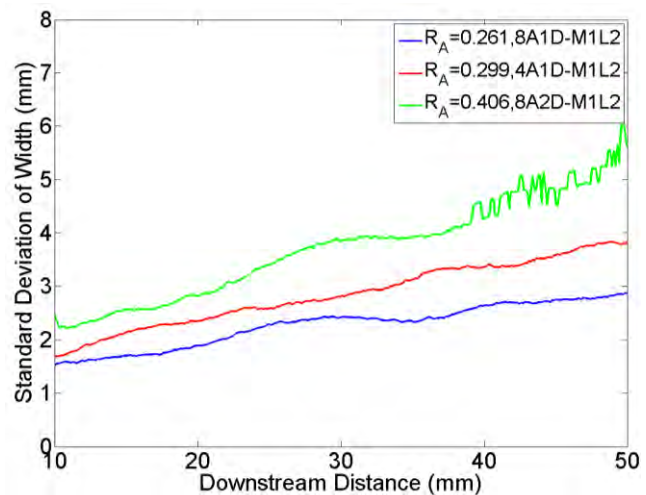


Figure 6. Higher R_A , tangential-to-total velocity ratio, (less swirl) produce sprays with more variability.

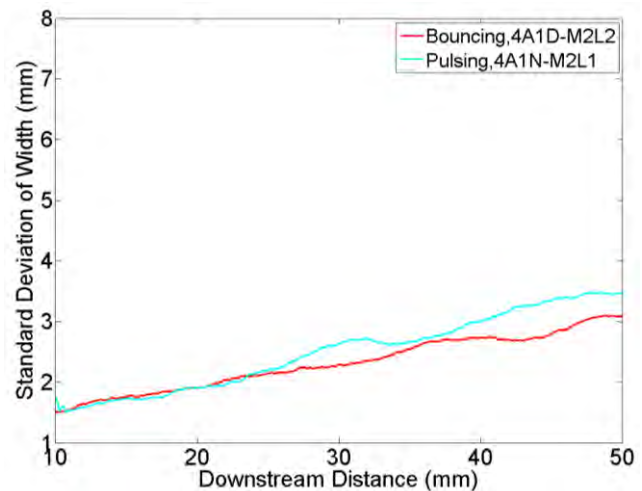


Figure 7. The standard deviation of two sprays with different characters of unsteadiness are very similar.

instabilities. All of the sprays shown in Figs. 4 and 5 exhibit some amount of pulsing behavior; all those in Fig. 4 also have some oscillatory-like behavior where the centerline changes in time and axial distance. The lower swirl case (8A2D-M1L2) has more variation, i.e. is less stable, than sprays with similar momentum flux ratios. This variation is captured in the standard deviation of the width (Fig. 6). Qualitatively, movies of the no swirl case imply that this spray is also less steady than its high-swirl counterpart; however, no measurements are available. The higher instability of the no-swirl spray is not surprising since, as discussed in a later section, the film being atomized is also very unstable without swirl [5]. The centripetal acceleration stabilizes the film and, therefore, the spray. The swirl also increases the residence time of the liquid in the cup: this increase is believed to be a main reason for the better atomization quality in swirling injectors. The stabilization of the film does not greatly impede atomization as shown by a simple atomization model published earlier [4]. From this model, aerodynamic forces are $O(3)$ larger than the centripetal forces (the other forces, viscosity and surface tension, are even smaller) [5]. The increased residence time far outweighs the small penalty in atomization caused by the swirl and aids performance by stabilizing the spray.

Because there are two different unsteady behaviors—pulsing and bouncing (oscillatory-like centerline movement)—observed in these sprays, it is necessary to establish that the change in standard deviation is not due to these differences in the type of behavior. Particularly, since the width is being presented, it should be established that the bouncing sprays do not have less variation than pulsing sprays purely due to the behavior difference. Two sprays which had markedly different unsteadiness—one which predominately pulsed with little change in centerline and one with changes in centerline and only a small amount of pulsing—were compared. The difference in behavior was due to changes in the lip geometry although there was a small difference in mass flow rate between the two. These geometry changes did very little other than alter the unsteady behavior of the spray—spray quality and width were comparable. As shown in Fig. 7, the sprays also have very similar standard deviation in width despite their dissimilar unsteady behaviors. While the standard deviation is similar, the rate of change and character of the unsteadiness is different as a result of the general character of the unsteadiness. So, differences in standard deviation seen in other tests are not solely explained by changes in the type of unsteady behavior the spray is exhibiting.

Finally, there is no measurable difference in the width of the three sprays shown in Fig. 4. This result is contrary to what might be expected and the findings from simplex and coaxial swirl injectors. The fact that the atomization occurs within the injector cup is the reason that the width is not affected. Once stripped from the film, the droplets rapidly come to equilibrium with the gas. Because the gas does not pick up much of the film's swirl, the droplets quickly lose their tangential velocities and, therefore, do not acquire much of a radial spread after exiting the injector. Only large structures are able to maintain some tangential velocity.

EFFECT OF MOMENTUM FLUX RATIO (GAS FLOW RATE)

The momentum flux ratio is the single most important nondimensional parameter for determining the atomization efficiency of a GCSC injector [5]; it is a measure of the aerodynamic forces in effect during the atomization process. A change in momentum flux ratio could impact the spreading of the spray in two ways. First, the less momentum the gas has in relation to the liquid, the more the gas may be altered by the liquid. So, like with increased liquid swirl number, the gas could be expected to acquire some tangential component to its velocity at low momentum flux ratios. Secondly, the lower the ratio, the longer the film and, therefore, the greater time the film and gas are in contact with one-another. Again, like with swirl, while this contact could transfer more tangential velocity to the gas, it is also likely to do the opposite and "straighten" the liquid flow more. Because the impact to the width with changes in swirl was seen to be small, changes due to momentum flux ratio are expected to be even smaller and, therefore, not measurable. Two different sets of tests with similar swirl and liquid mass flow rates but different momentum flux ratios (i.e., different gas velocities) were compared. Each set did not have a measurable difference in width. Fig. 8 gives an example of the widths for one sets of tests.

While there is no change in width, atomization quality decreases with a decrease in momentum flux ratio as would be expected from the scale modeling [4]. The sprays with lower momentum flux ratios



MFR=67, 4A1D-M1L2



MFR=81, 4A1D-M2L2

Figure 9. Lowering the momentum flux ratio (MFR) increases the size and number of liquid structures on the periphery of the spray.

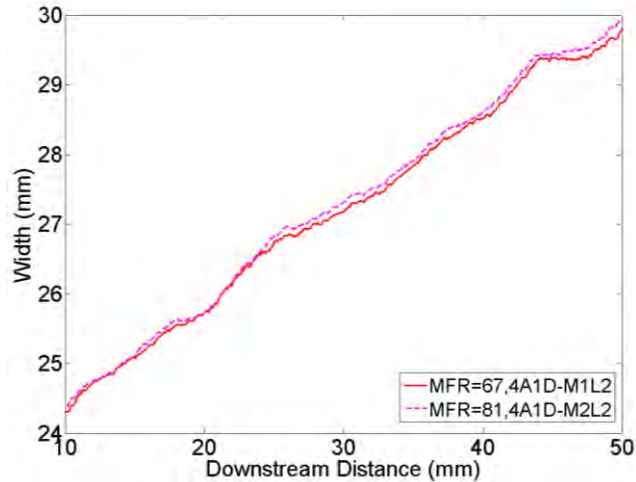


Figure 8. A change in momentum flux ratio, while the swirl and liquid flow rates are nearly constant, has no measurable effect on spray width.

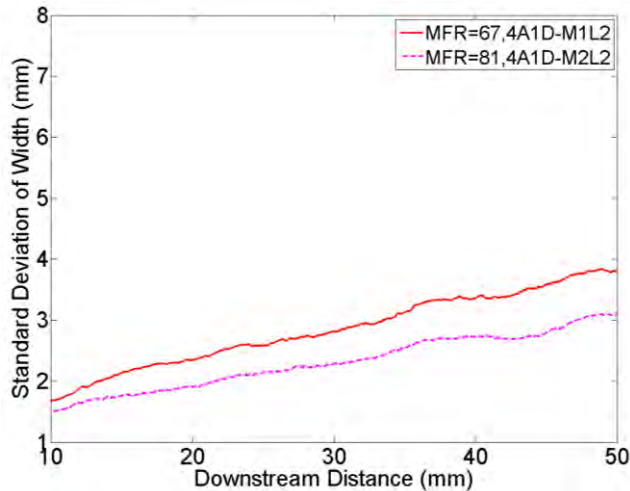


Figure 10. Despite nearly identical widths, the standard deviation of the lower momentum flux ratio case is slightly larger.

have larger droplets along their periphery. Figure 9 compares the same two sprays shown in Fig. 8 illustrating this finding. The momentum flux ratio also changes the stability of the sprays. Changes in the character of the instabilities with changing momentum flux ratio were reported in an earlier study [13]. Similar results are seen here with sprays behavior changing from pulsing to bouncing as the momentum flux ratio is altered. In addition to the change in character, the amount of variation is also affected. Sprays with lower momentum flux ratios have somewhat greater variation as shown by an increase in standard deviation (Fig. 10). As discussed above, the standard deviation difference is not a measure of the change in the stability character it is indicative of an actual increase in variability not just a difference in the type of variability. The change in standard deviation would be expected to be larger if the momentum flux ratios were lower, since earlier studies found the film was most unstable at lower momentum flux ratios.

EFFECT OF LIQUID MASS FLOW RATE

Unfortunately, the current series of test cases does not allow comparison of different liquid flow rates with the swirl and momentum flux ratios held constant. Some conclusions can still be drawn by comparing sprays with different swirl numbers or slightly different momentum flux ratios. According to the developed scaling laws and the observed film behavior, the atomization quality should not be impacted by liquid mass flow rate as long as the momentum flux ratio is held constant [4, 5]. A comparison of two sprays with similar momentum flux ratios and the same swirl but different lip geometries (Fig. 11) supports this theory. However, the flow rates for these two cases is relatively unchanged. The only comparisons that can be made with large changes in liquid flow rate also have very different R_A . This comparison gives the opposite result (Fig. 12). However, given that the swirl, particularly at the lowest swirl (highest R_A) seems to impact the atomization quality, it is possible that the difference in quality is a result of the swirl and not the liquid flow rate. More conditions will be needed to draw any strong conclusions.

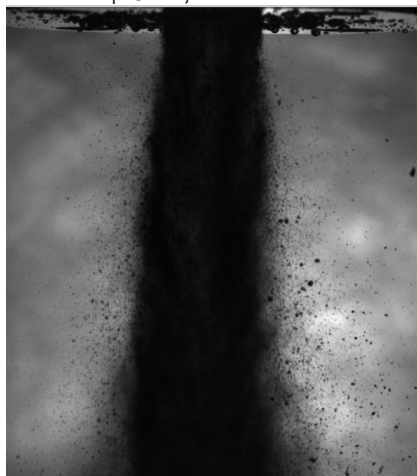
Simplex and coaxial swirl injectors have spray angle increases with liquid mass flow rate [6, 7]. This increase is a result of the increased velocity and, in general, film thickness at the exit of these injectors when the flow rate increases. Because the atomization of GCSC injectors occurs within the injector cup, these devices should be less influenced by liquid mass flow rate, assuming the momentum flux ratio remains unchanged. However, an increase in mass flow rate does mean an increase in the



$m_l=32.7$, 4A1N-M2L1



$m_l=36.2$, $R_A=0.261$, 8A1D-M2L1



$m_l=45.4$, 4A1D-M2L2



$m_l=60.4$, $R_A=0.406$, 8A2D-M2L2

Figure 11. A change in liquid flow rate (m_l), but very little change in momentum flux ratio, has no obvious impact in the atomization quality. Here the swirl is the same but the lip geometry has changed.

Figure 12. When both the swirl and liquid flow rate change there is a definite difference in atomization quality. However, whether this change is due to swirl or mass flow rate is currently unclear.

number or size of droplets within the gas core. This additional mass might be expected to produce some increase in the size of the “dark core” imaged by shadowgraphy. And the change in liquid flow rate does appear to impact the spray width (Fig. 13) at least in the initial 50 mm downstream. These changes are at the edge of what is measurable in the current system, but they are larger than those observed with alterations of the other parameters examined. Furthermore, as shown in Fig. 13, the differences exist at measurable levels even for the set of conditions where the swirl is constant. This finding has some impact on injector design and throttling engines. A decrease in the width would create less interelement mixing in a rocket engine. This deficit could be remedied during the design phase by moving elements closer together. However, if the change in width is produced by mass flow changes due to engine throttling then a change in spacing is not an option. Care should be taken in throttling such that large differences in liquid flow rate are not encountered. Some flexibility in throttling does exist with respect to the gas flow rate, however, (provided the momentum flux ratio remains large enough to ensure good atomization efficiencies) since the width does not vary much with momentum flux ratio.

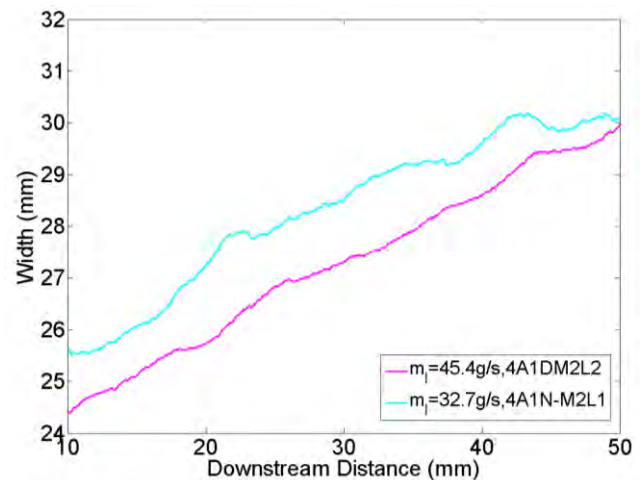


Figure 13. The spray width increases for sprays with larger liquid mass flow rates.

NUMBER OF INLETS

The number of inlets is not varied independently in the current set of experiments. However, two similar swirl levels are achieved between a 4- and 8-inlet geometry. As mentioned earlier, a change in inlet number was shown to have very little effect on a pressure swirl atomizer [6, 7]. There is no reason to believe a GCSC injector would be more susceptible to changes in the number of inlets. This assertion is easily verified by comparing two cases with similar mass flow rates, momentum flux ratios and swirl. Even with the slight difference in swirl, the two cases (4A1D-M1L2 and 8A1D-M1L2) shown in Fig. 4 appear similar in character. There is no measurable difference in width and the standard deviations are similar. So, there does not appear to be any strong impacts of changing the number of inlets. However, others have claimed that staggering the inlets can prevent feedback through the liquid flow system and reduce the likelihood of combustion instability [7]. The cold flow results cannot indicate whether or not this finding is true, but they show that the designer has latitude to change the inlet diameters and numbers without affecting the spray.

SIMULATIONS OF NO-SWIRL ATOMIZATION

Scale models and design guidelines are important tools for reducing the cost of new engine design. The availability of reliable computational models could reduce costs even further. However, simulating multiphase flows with droplets and a liquid-gas interface is not simple and currently not cost-effective for even relatively simple injectors. The high shear and swirling nature of the GCSC injectors present even more difficulties. Simulations are being done of these injectors, but the current, instantaneous results are still preliminary and do not yet agree with experimental results. Preliminary results are given here to provide a sense of the complexity, successes and shortfalls in the computational modeling of these flows.

The simulated flow discussed here has no swirl. Because swirling flows are rarely axisymmetric, the addition of the swirl complicates the modeling tremendously. However, as alluded to above, a lack of swirl has a large impact on the film stability and atomization efficiency. A flat injector was machined to

further examine the film development and atomization in cases with no swirl. While not directly applicable to rocket engines, this set-up is easier to image and allows better access for turbulence and droplet measurements at the inception of atomization (before large number of droplets result in optical densities that prevent laser measurements). These measurements are planned for the future along with flat geometry simulations; the current computational modeling is axisymmetric. The flat-geometry experimental results agree with the axisymmetric experiments presented in earlier literature [5]: the corrugation of the film increases dramatically from the swirl cases including increases in the size of observed disturbances, filling the volume under the lip is difficult at low flow rates leading to uncertain conditions at liquid-gas contact, and there is increased gas entrainment into the film (bubbles).

The simulations were conducted using FLUENT. The VOF model was used for the liquid phase with compressible gas flow and variable, explicit time stepping [14]. The explicit time stepping was chosen because the implicit time stepping was not converging between time steps. A grid-independence study was performed for the single-phase flow; multiphase grid independence is not straight forward and may not be achievable. An examination of turbulence models was also conducted; the k-epsilon model was chosen from the results. Regardless of initial conditions, the simulations require some “start up time” where the flow of the liquid is developing and, therefore, not realistic. During this time period, very large droplets (“blobs”) of mass are observed. As time increases, the mass involved in these large structures decreases until it reaches a “steady” state—not without change but randomly distributed about a constant value. The 0.1 seconds simulated to date is nearing but may not yet have reached this state. Still, by this point the simulations show some of the main qualitative components of the film: the film length is very

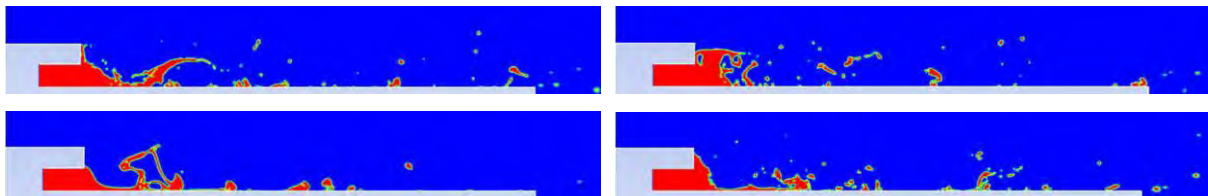


Figure 14. Time increases moving from left to right, top to bottom in this time series from a computational simulation with $m_g=125$ g/s and $m_l=72$ g/s. The time steps are each approximately 2 milliseconds.

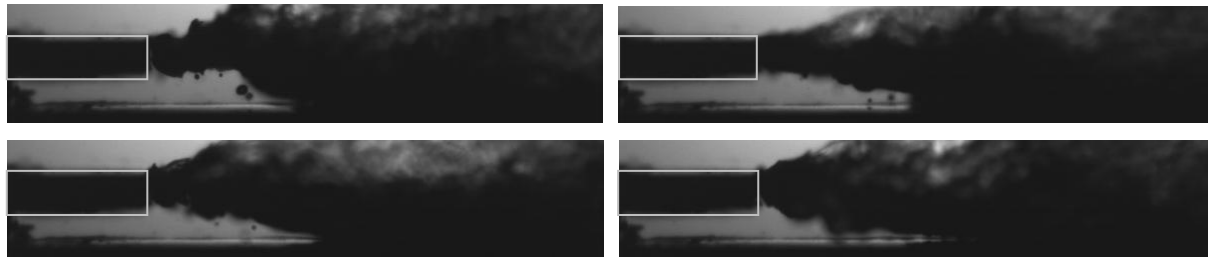


Figure 15. A sample temporal series from the flat-geometry injector experiments is given with the same 2 millisecond timing as in Fig. 14. Here the $m_g=15.5$ g/s and $m_l=32.2$ g/s.

unsteady, and large disturbances are observed on the surface. There are still some departures, however. The simulations do not show the amount and size of bubbles created by the experiment. The frequency of the film length variations also appears to be an order of magnitude (or more) larger than those observed in the experiment. Figure 14 shows a typical time sequence from the simulations. Figure 15 shows a time sequence from the experiments. In these pictures, the film is lit from the back, to the light areas are film and the dark area are spray. Again, while there is some qualitative agreement, quantitative agreement has not yet been achieved.

CONCLUSIONS

The effects of swirl and other design parameters on the spray of a gas-centered swirl coaxial injector were examined. Only a handful of cases were available making the results preliminary, but

several interesting trends which can be used to improve design criteria have emerged. To improve the quality and stability of the spray, a designer should aim for high swirl levels, high momentum flux ratios and lower liquid mass flow rates. These choices increase the stability and atomization quality of the spray. The width of the spray is not measurably changed with swirl number or momentum flux ratio. The width is altered by the liquid mass flow rate, however, with higher flow rates producing slightly wider sprays. While slight, this change in width could have some impact on mixing and performance during throttling if the liquid mass flow rate was greatly varied. Finally, the number of inlets does not appear to have an impact on the spray character, behavior or width. The engine designer, therefore, has a choice to achieve the desired swirl level and hole size.

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